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## HBT and Fluctuations: Recent Results

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An overview is presented of the latest results of HBT and fluctuations studies in heavy ion collisions reported during the Quark Matter 2001 Conference.

### 1. Introduction

The study of small relative momentum correlations, a technique also known as HBT [1] interferometry, is one of the most powerful tools at our disposal to study complicated space-time dynamics of heavy ion collisions [2]. It provides crucial information which helps to improve our understanding of the reaction mechanisms and to constrain theoretical models of heavy ion collisions. It is also considered to be a promising signature [3,4] of the Quark Gluon Plasma (QGP). Interpretation of the extracted HBT parameters in terms of source size and lifetime is more or less straightforward for the case of chaotic static sources. In the case of expanding sources with strong coordinate space-momentum correlations (due to flow, etc.) the situation is more difficult, but the concept of a homogeneity length [5] provides a useful framework for the interpretation of data.

### 2. HBT Results

New data from the NA45 [6] (CERES Collaboration) and NA49 [7] experiments at CERN shed new light on the evolution of the reaction dynamics at SPS energies. Both collaborations showed results from systematic studies of HBT parameters in the Pratt-Bertsch parameterization [8,9] for Pb+Pb(Au) collisions at 40A GeV. Taking into account the preliminary status of both analyses, the agreement between them is fairly good. The NA49 Collaboration analysis shows a striking similarity (including detailed  $K_T$  dependence, where  $K_T$  is the average transverse momentum of a pair) between the radius parameters at 40 and 160A GeV. This, coupled with results of the transverse radial flow analysis [10], suggests that the reaction dynamics, despite the difference in the initial energy density and final state multiplicities, are rather similar.

The STAR Collaboration has shown [11] preliminary results of an extensive analysis of the pion (both  $\pi^+$  and  $\pi^-$ ) correlation functions measured at RHIC in Au+Au collisions at  $\sqrt{s_{NN}}=130$  GeV. While an increase in the radius parameters with charged particle multiplicity was more or less expected, the observed  $K_T$  dependence, shown in Fig. 1, is somewhat of a surprise. The general trend of the HBT radius parameters with  $K_T$  is consistent with strong coordinate space-momentum correlations due to transverse

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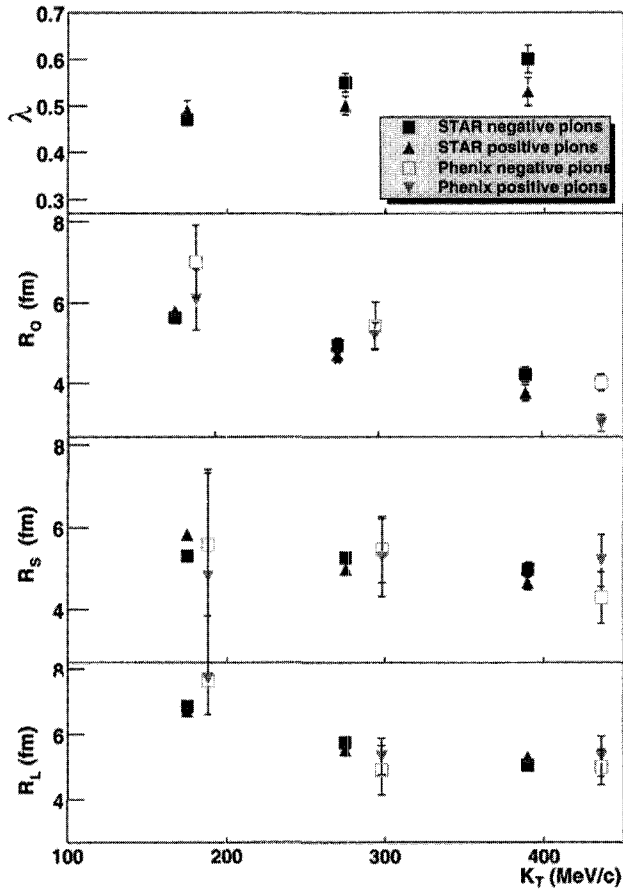


Figure 1. Preliminary data on  $K_T$  dependence of pion HBT parameters reported by STAR [11] and PHENIX [16] Collaborations.

flow, however, the  $K_T$  dependence of the ratio of  $R_O/R_S$  contradicts the model predictions [3,12]. Model calculations predict the ratio to be greater than unity due to system lifetime effects which cause  $R_O$  to be larger than  $R_S$ . They also predict that the  $R_O/R_S$  ratio increases with  $K_T$ . Such an increase seems to be a generic feature of models based on the Bjorken-type [13], boost-invariant expansion scenario. Hence, it is unexpected that the experimentally observed ratio is less than unity and is decreasing as a function of  $K_T$ . Currently, it is far from clear what scenario leads to such a puzzling  $K_T$  dependence. In principle, the observed behavior is consistent with the creation of an opaque source [14] in the collisions. However, to address this possibility seriously one needs to perform a detailed analysis of the pion correlation function in the Yano-Koonin-Podgoretski parameterization [15].

Preliminary results of the HBT analysis presented [16] by the PHENIX Collaboration agree with the STAR results within error bars but comparison of these data does not provide a sufficient cross check due to the limited statistics of the first analysis. Further cross checks of these results by other RHIC experiments are very desirable.

The new results from RHIC and from lower energy running of the SPS significantly extend the study of HBT systematics. Figure 2 shows the evolution with energy of the Pratt-Bertsch parameters of the two-particle correlation functions measured [6,7,11,16–19] in central heavy-ion collisions. It is evident from the figure that HBT parameters change most rapidly at the AGS energies ( $\sqrt{s_{NN}} \approx 2\text{--}5$  GeV). The pronounced decrease with energy which is observed is driven by an increase in transverse flow. Growing coordinate space-momentum correlations lead to a shrinking apparent source size. Saturation of the flow velocity [10] (which is reached around the highest available beam energy at the AGS) leads to a different evolution of the HBT parameters in the SPS energy range ( $\sqrt{s_{NN}} \approx 10\text{--}20$  GeV). One can see that transverse HBT radii change very little at the SPS. The observed behavior strongly suggests that the HBT correlation functions directly reflect properties of the collective transverse flow generated in the collision.

A consistent picture seems to emerge from the systematic behavior of the energy dependence of the pion phase space densities reported during the conference. Preliminary results shown [11] by the STAR Collaboration are consistent with hypothesis of a universal freeze-out phase space density [20] at RHIC energies. The  $p_T$  dependence of the phase space density at midrapidity at RHIC clearly rules out a static thermal source and is consistent with a Bose-Einstein distribution modified to take into account radial flow. The flow velocity extracted from the analysis of the  $p_T$  dependence is quite high ( $\approx 0.58c$ ) with a freeze-out temperature of about 94 MeV.

Study of the freeze-out phase space density by the NA45 Collaboration [6] also confirmed a universal phase space density at 40A GeV. It was also reported that the phase space density seems to be independent of centrality.

The E895 Collaboration showed [21] that at AGS energies (2–8A GeV) the phase space density distribution is lower than the “universal”, one gradually approaching the universal distribution with increasing energy.

It was evident during the conference that studies of the correlations of neutral ( $\Lambda$ ,  $K^0$ ) strange particles has attracted a lot of attention. Even though details of the final state interaction of neutral strange particles are not very well known, complicating the interpretation of these measurements, the physics which can be accessed via this type of

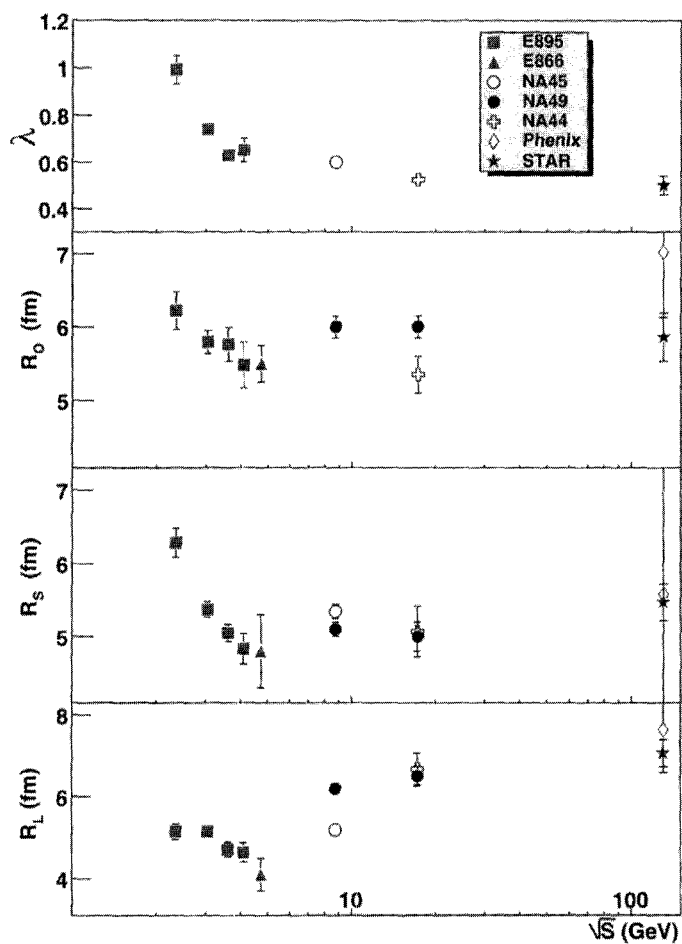


Figure 2. Measured Pratt-Bertsch parameters of two-particle correlation functions from central heavy-ion collisions at different energies [6,7,11,16–19]. See text for details.

correlations is attractive. In combination with measurements of strange particles yields and spectra they can provide valuable new information about strangeness dynamics in the collision.

From the experimental point of view such correlations have certain advantages. Being neutral there are no Coulomb repulsion problems, and two-track resolution problems are largely avoided as well. They are also less influenced by the resonance decays. On the other hand such studies pose significant experimental challenges since they usually require sizeable datasets and large acceptance detectors due to the relatively low yields and reconstruction efficiencies of neutral strange particles. Such data were generally unavailable until now in heavy ion collisions.

The NA49 Collaboration presented [7] preliminary analysis of the  $\Lambda$ - $\Lambda$  correlations from Pb+Pb collisions at 158A GeV. The shape of the measured correlation function shows a pronounced dip at low relative momentum which is consistent with Fermi-Dirac statistics of  $\Lambda$  hyperons. There seems to be evidence of a weak repulsive  $\Lambda$ - $\Lambda$  potential which may have consequences for H-dibaryon searches. This interesting topic certainly requires further investigation.

The STAR Collaboration showed preliminary results of the analysis of  $K^0$ - $K^0$  correlations measured in Au+Au collisions at  $\sqrt{s_{NN}}=130$  GeV. The extracted Gaussian radius  $R_{inv} \approx 6 fm$  is consistent with pion HBT measurements.

The E895 Collaboration studied another exotic system,  $\Lambda - p$ , in Au+Au reactions at lower AGS energies. Preliminary results [21] are consistent with a strong attractive interaction between the proton and the  $\Lambda$  hyperon, but the measured coordination cannot be described by the simple source modes with an Urbana type potential [22].

The E895 Collaboration also showed [21] results of the HBT analysis in the impact-parameter-fixed coordinate frame. In this approach event-by-event information about the orientation of the reaction plane is combined with information from two-particle correlations. Such an analysis is not only sensitive to the homogeneity length and the time, but also to the tilt of the source in the reaction plane. Experimental access to this level of geometrical detail of the freeze-out distribution is unprecedented, and represents a new opportunity to study dynamics of heavy-ion collisions.

### 3. Fluctuations

In recent years the analysis of event-by-event fluctuations has emerged as a key focus in experimental studies of the relativistic heavy ion collisions.

The NA45 Collaboration showed [6] analysis of the mean transverse momentum fluctuations in Pb+Au central collisions at 40, 80 and 158A GeV. They reported the observation of small ( $< 3\%$ ), but statistically significant dynamical fluctuations at all three energies. The observed  $\Phi_{p_T}$  value [23] is  $\approx 8$  MeV at 158A GeV. This interesting result contradicts the small  $\Phi_{p_T} \approx 0.6$  MeV/c value reported earlier [24] by the NA49 Collaboration. Clearly, this discrepancy requires further study.

The NA49 Collaboration reported [7] preliminary results of the analysis of the event-by-event charge fluctuations in central Pb+Pb collisions at 40 and 158A GeV. They studied fluctuations of ratios of the number of positive and negative hadrons as a function of the width of the pseudorapidity window and applied acceptance corrections following the

procedure suggested by Bleicher, Jeon and Koch [25,26]. The fully corrected results are somewhat surprising: fluctuations of charge particle ratios at both energies are similar and are consistent with the fluctuations produced in a pion gas. Naively one would expect at SPS energies somewhat smaller fluctuations consistent with a resonance gas or even perhaps with the Quark Gluon Plasma.

The WA98 Collaboration presented results of the search for localized fluctuations in the multiplicity of charged particles and photons produced in Pb+Pb reactions at 158A GeV. They reported individual fluctuations in photon and charged particle multiplicities, but no correlated event-by-event fluctuations of  $N_\gamma - N_{ch}$ .

The NA44 Collaboration reported [27] preliminary results of the search for local fluctuations in the number of charged particles using a novel event texture analysis. No evidence of critical fluctuations was found.

For RHIC, the STAR Collaboration reported [28] preliminary results of an extensive event-by-event fluctuations analysis. Data presented by STAR included an investigation of the charge-dependent and charge-independent  $\langle p_T \rangle$  fluctuations individually, as well as the overall  $\langle p_T \rangle$  fluctuations. A significant excess in the level of fluctuation of  $\Delta\sigma_{p_T} \approx 35$  MeV/c beyond the statistical expectation was observed in the charge-independent analysis. Also, a somewhat smaller but still statistically significant excess was observed in the charge-dependent analysis. STAR also studied the centrality dependence of these excess fluctuations, and observed a hint of a decrease with centrality in the charge-dependent part. The results of multiplicity fluctuation analysis shows no evidence for the fluctuation suppression predicted to occur with rapid hadronization of a QGP.

Event-by-event fluctuations also drew a lot of attention from theorists. Most of the theoretical studies reported at this conference were devoted to the fluctuations of so-called “conserved quantities”: charge, baryon number, strangeness, etc.

Koch discussed the theoretical situation regarding the fluctuations of conserved quantities in general and charge ratios in particular. He pointed out the effects of limited detector acceptance and the importance of related corrections. It was apparent during the conference that current theoretical interest is aimed at studying the “survivability” of the proposed observables in a realistic situation. Most of the results discussed were concerned with studies of the influence of system expansion and limited experimental acceptance. These were discussed in talks by Asakawa [29], Stephanov [30], Gavin [31].

Pratt [32] presented a new observable for determination of the nature of hadronization in heavy ion collision - balance functions. A balance function describes the conditional probability that a particle in the momentum bin  $p_1$  will be accompanied by a particle of opposite charge in the bin  $p_2$  [33]. Balance functions probe hadronization by quantifying charge correlations in momentum space, potentially allowing us to distinguish scenarios with QGP formation from purely hadronic ones. First experimental attempts to apply this observable to heavy ion collisions are underway.

#### 4. Conclusions

Many new and interesting HBT results have appeared since last Quark Matter. Combined results from the AGS, SPS and RHIC afford systematic studies of the evolution of the HBT parameters with beam energy. Presentations of the first results from RHIC

experiments were among the highlights of the conference. The most intriguing feature of the preliminary HBT results from RHIC is the  $K_T$  dependence of the  $R_O/R_S$  ratio reported by the STAR Collaboration. It is not yet clear what physics leads to the kind of dependence reported by STAR.

It would be interesting to perform measurements between the AGS and SPS energy domains, which may be a transition region in terms of HBT systematics. It would also be useful to probe the energy range between the SPS and RHIC. Such measurements will significantly extend our understanding of spatial-temporal evolution of heavy ion collisions.

The situation with fluctuation measurements at the SPS is not yet clear and further experimental and theoretical effort is needed to resolve the existing ambiguities.

Preliminary fluctuations results from RHIC are tantalizing and warrant further investigation.

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